Inductive monopole detector employing planar high order superconducting gradiometer coils

C. D. Tesche, C. C. Chi, C. C. Tsuei, and P. Chaudhari
IBM T. J. Watson Research Center, Yorktown Heights, New York 10598

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The characteristics and performance of a family of high-order planar gradiometer detectors for inductive detection of magnetic monopoles are discussed. Conventional superconducting magnetometers used for monopole detection must be operated in an extremely stable, low field environment. This places a severe restriction on the cross-sectional area of such detectors. However, planar gradiometer detectors permit the use of relatively large area detectors in coincidence without requiring a corresponding increase in the stability of the ambient field.

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A single event observation of a magnetic monopole candidate using the superconductive induction technique has been reported by Cabrera.[1] The confirmation of the existence of a substantial flux of massive monopoles would have a far reaching impact on grand unification theories and cosmology. However, conventional superconducting magnetometers used for monopole detection must be operated in a magnetic field stabilized such that the variations in the ambient flux linking the detector are small compared to the expected monopole signal of $2\Phi_0$. As a result, ultralow magnetic field environments are usually required, placing a severe restriction on the cross-sectional area of such detectors. Variations in the ambient field may be suppressed by surrounding the detector with a superconducting shield. However, flux jumps occurring within the shield can produce a signal indistinguishable from that of a monopole. In addition, persistent screening currents generated in the shield by the passage of a monopole through the system can link substantial flux into the detector. As a result, the magnetic charge of the monopole cannot be determined without an independent measurement of the particle trajectory. Conversely, if the monopole signal is assumed to be $2\Phi_0$, spurious events which generate a change of the net flux through the detector coils of less than $2\Phi_0$ cannot be distinguished from monopole candidates.

We propose the following solution to this problem. The detector coil is twisted into a set of coplanar loops. As a result, the detector is relatively insensitive to flux generated by sources located on the shields. However, a monopole trajectory would link only one of the loops. As a result, the signal flux is unchanged.

The pick-up coil for our detector consists of a set of coplanar superconducting loops connected in series. The total pick-up inductance L_p is connected in series with a superconducting coil of inductance L_c which is tightly coupled to an rf superconducting quantum interface device (SQUID).[2] The passage of a monopole through L_p generates a change in the persistent screening current flowing around the coil of

$$\Delta I = (2\Phi_0 - \Phi_s)/(L_p + L_c - M), \tag{1}$$

where M is the mutual inductance between the detection coil and the superconducting shield used to stabilize the field. The flux Φ_s is produced by the persistent screening currents generated in the shield as the monopole passes through the superconductor. The pick-up coils are designed so as to minimize the contributions from M and Φ_s. As a result, the detector is also extremely insensitive to the motion of flux which may have been trapped in the shield as it was cooled into the superconducting state. This is an important property of the detector design since it permits the relaxation of the constraint on the ambient magnetic field.

The coils are part of the following hierarchy. First, consider a one-dimensional chain of coplanar loops. Suppose that all the loops are of area ds, equally spaced by Δx along the x axis. The net flux linking the entire array of 2^m loops is

$$\Phi = \sum_{k=1}^{2^m} S(k)\phi(k). \tag{2}$$

The flux $\phi(k) = B_n(x_k)\, ds$, where the normal component of the field, B_n, is evaluated at $x_k = x_0 + k\Delta x$. The orientation function $S(k) = \pm 1$ is determined as follows. The distribution of the flux trapped in the shield can be quite arbitrary, even though the geometry of the shield is well defined. Thus, we use a Taylor series expansion of the field. In this expansion, the Pth derivative of B_n is multiplied by $(k\Delta x)^P$. Thus, if the $S(k)$ satisfy

$$\sum_{k=1}^{2^m} k^P S(k) = 0, \tag{3}$$

then the Pth derivatives of the field will not contribute to the net flux linking the detector. Since the field generated by sources located on the shield falls off inversely with distance, the pick-up coil will become less sensitive to these sources as P is increased.

A detector consisting of a single loop (order $N = 0$) is sensitive to all the terms in the expansion of the field. The first order detector ($N = 1$) is insensitive to the uniform component of B_n provided all the $S(k)$ sum to zero. The lowest value of m which satisifes this constraint is $m = 1$, with $S(1) = 1$ and $S(2) = -1$. The higher order detectors can be determined by induction. The detector of order $N + 1$ is generated by taking the sequence for the detector of order N twice in succession, negating each term in the second block.[3] The pattern for $S(k)$ for the first four detectors are $(+)$ for $N = 0$, $(+\ -)$ for $N = 1$, $(+\ -\ -\ +)$ for $N = 2$, and $(+\ -\ -\ +\ -\ +\ +\ -)$ for $N = 3$. A two-dimensional array of detectors is generated as follows. If we require the detector to consist of equal area loops located on a symmet-

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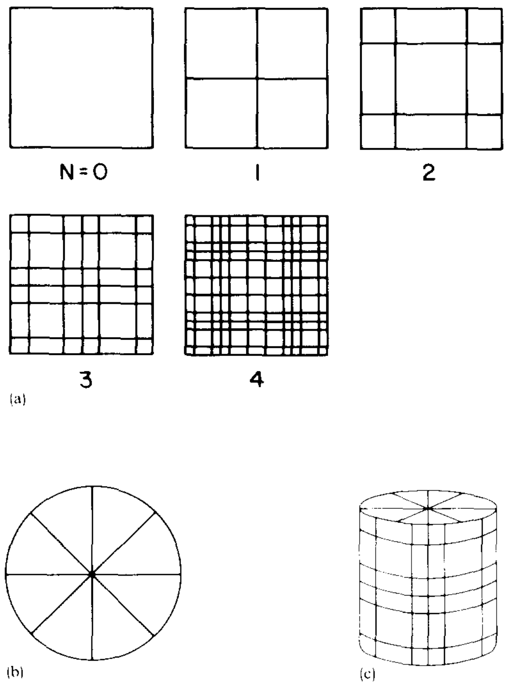

FIG. 1. Planar gradiometer coils with (a) rectangular and (b) polar symmetry, and (c) a cylindrical array of independent coils.

ric grid in the xy plane, the orientation function is $S_{xy}(j,k) = S(j)S(k)$. An array of order $N \times N$ is insensitive to all components with derivatives of order $P < 2N$.

Up to this point, the analysis presented can be applied to detectors other than superconducting magnetometers provided that the individual detectors are identical. In our case, since the detectors consist of loops of superconducting wire, adjacent loops which have the same orientation on the planar substrate may be joined, producing the detector patterns shown in Fig. 1(a). In addition, a hierarchy of detectors can be generated with polar, rather than rectangular symmetry [Fig. 1(b)]. Detectors in which the equal area constraint has been relaxed may also be constructed.[4] The characteristics of these detectors will be described in a future publication.

The flux linking a single loop of a square detector is

$$\phi_m = \int_{x_1}^{x_2}\int_{y_1}^{y_2} dx'dy'\,\mathbf{B}\cdot\hat{z} = \left(\frac{q_m}{4\pi}\right)\int_{x_1}^{x_2}\int_{y_1}^{y_2} dx'dy'z[(x-x')^2+(y-y')^2+z^2]^{-3/2}$$

The integral can be integrated explicitly. The result is

$$\phi_m = g(x_1,y_1) + g(x_2,y_2) - g(x_1,y_2) - g(x_2,y_1),$$

for

$$g(x_i,y_i) = \left(\pi\frac{q_m}{4}\right)\tan^{-1}\left(\frac{(x-x_i)(y-y_i)}{z\sqrt{(x-x_i)^2+(y-y_i)^2 1 z^2}}\right), \quad (4)$$

where the source is a monopole of charge $(q_m/4\pi)$ located at (x, y, z). The coordinates of the vertices of the square loop are $(x_1, y_1, 0)$ and $(x_2, y_2, 0)$.

The net flux linking a square detector of order N and total area D^2 is evaluated from Eq. (4). As an example, we plot in Fig. 2 the rms flux as a function of distance z of the

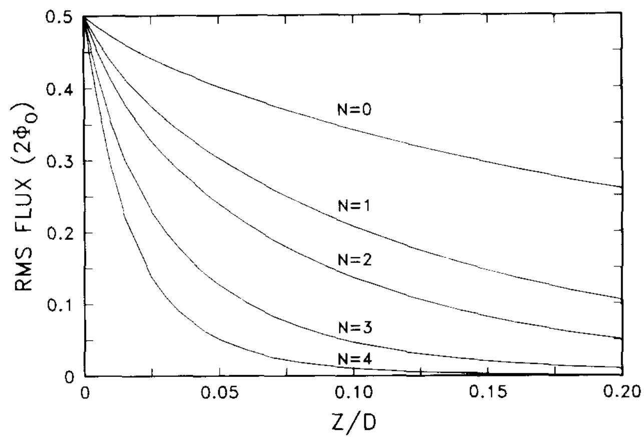

FIG. 2. Averaged signal flux as a function of distance z of the monopole source above a detector for orders $N = 0, 1, 2, 3, 4$.

monopole above the detector for orders $N = 0, 1, 2, 3, 4$. The flux has been averaged over all monopole locations (x, y, z) such that $(x, y, 0)$ lies within the detector. In the limit $z = 0$, the monopole passes through one of the detector loops. Thus, the signal flux approaches Φ_0 for all orders of N. At distances $z > 0$, the response to a point source falls dramatically with increasing N.

The response of a single square detector of order N which is located within a cylindrical superconducting shield to an isotropic flux of monopoles is determined by a Monte Carlo calculation. The screening currents generated by the passage of the monopole through the shield are approximated by replacing the shield and screening currents by a pair of isolated magnetic charges at the points of penetration of the shield. These sources link a flux Φ_s through the detector. In addition, a flux of $2\Phi_0$ or 0 linked into the detector by the incident monopole, depending on whether or not the trajectory passes directly through one of the detector loops. The net applied flux seen by the detector is thus either reduced below $2\Phi_0$ or increased above 0 by the screening flux Φ_s. The probability that a particular value of net flux will be observed for a randomly generated trajectory is plotted as a function of net flux in Fig. 3. The shield diameter is 17.5 cm and the area of the detector is 100 cm^2. The detector is located symmetrically within the shield in the plane perpendicular to the axis of the cylinder. Note that, as the order N is increased for constant detector area, the range of values of net flux corresponding to probable monopole events decreases. As a result, spurious flux jumps in the shields may be more easily identified.

Because spurious signals cannot be entirely eliminated, coincidence detection between at least two independent detectors is imperative. However, a pair of planar detectors must be separated sufficiently far apart so that the screening current ΔI generated in one loop does not link a flux which is a substantial fraction of $2\Phi_0$ into the other detector. Since those particles which intercept only one detector are not recorded as coincident events, the effective area for coincident detection decreases as the separation between the detectors increases. However, if high order derivative detectors are used, the separation between the detectors can be reduced to on the order of the individual loop size, rather than that of

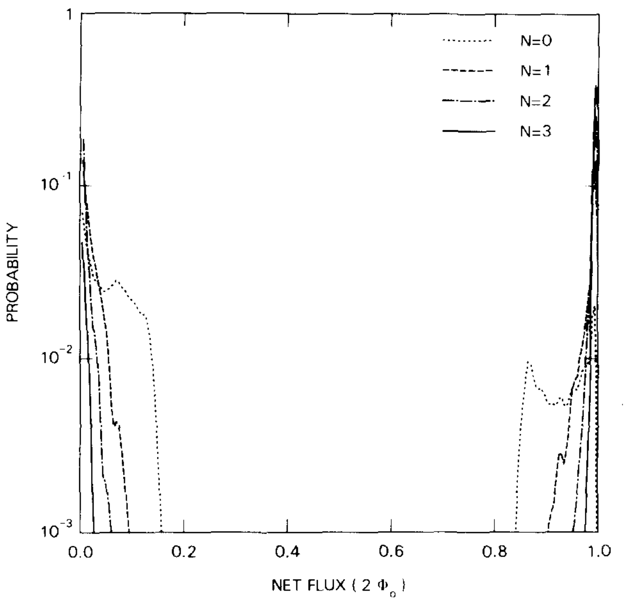

FIG. 3. Detector profiles for square detectors of orders $N = 0, 1, 2, 3, 4$ located within a cylindrical superconducting shield. The probability of observing a net flux is plotted as a function of net flux for an isotropic flux of monopoles. The detector area is 100 cm^2 and the shield diameter is 17.5 cm.

the entire detector, without significant flux linkage. Thus, the effective detector area can be increased without sacrificing the independence of the detectors. This property is exploited in the detector described below.

In addition, independent detectors can be oriented such that all possible trajectories result in a coincidence detection. For example, of six detectors located on the faces of a cube, two and only two must record an event if the particle is to be a massive monopole. The mutual inductance between adjacent (orthogonal) faces is zero. The derivative configuration reduces the mutual inductance between parallel faces to an insignificant value. The effective planar area for coincidence detection is $3D^2$. A cylindrical detector of this type is shown in Fig. 1(c).

A prototype pair of planar gradiometer coils was fabricated as follows. No μ metal shielding was used. Helmholz coils were used to reduce the ambient field to 10 mG over the detector area. This field is more than five orders of magnitude greater than that previously used.[1] A single 2.5-mil-thick lead foil shield, 17.5 cm in diameter and 60 cm high, was used to stabilize the ambient field and to provide a longitudinal shielding factor of 10^5. The shield was mounted over a glass cylinder and was closed at the bottom. The sides of the shield were welded together, and the shield cooled down in direct contact with liquid helium.

The detector coils were wound out of 5-mil niobium wire glued into grooves machined into planar substrates. Phenolic was used for the substrate material for convenience. The inductances of the coils were measured with the coils mounted inside the lead foil shield. The outside dimensions of the square coils were 10×10 cm, yielding an individual detector area of 100 cm^2. Detectors of order $N = 0, 1, 2, 3$ and 4 were tested. The inductance of the coils increased roughly linearly with the total length of wire used in the coils. Thus, the length of wire tended to grow like 2^N in the limit of large N for equal area coils, and like $2N$ for coils with arbitrary cell areas. From Eq. (1), the signal decreases with increasing input coil inductance, and thus decreases with increasing order N. The noise was also observed to decrease with increasing order. The best signal-to-noise ratio for the equal area coils was achieved for a detector with $N = 3$, $L = 3.4\,\mu$H. A pair of such detectors was operated in coincidence in this system with an effective area of 50 cm^2 and a signal-to-noise ratio of 10:1 in a 1-Hz bandwidth. Mechanical shifts of the coils produced by stress release within the phenolic were observed to produce flux jumps, pointing up the necessity of using materials which are mechanically stable in a cryogenic environment. In addition, deliberately introduced rf pulses (from a Tesla coil) were seen to produce permanent, and in some cases, coincident, flux jumps. However, no spontaneously occurring signals consistent with a monopole event were observed in over 80 days of observation.

The possibility that a spurious flux jump might be produced by stress release within the detector or shields, or by rf induced flux motion cannot be entirely eliminated, even if mechanically stable detectors are operated in a carefully shielded, low magnetic field environment. However, the use of high-order gradiometer detectors operated in coincidence will increase the reliability of inductive monopole detectors. In addition, the area of such detectors can be increased without demanding a corresponding increase in the stability of the ambient field. A detector incorporating coils of this type is presently under construction. Statistical results will be reported later.

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